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THE USE OF "INSOLUBLE" SALTS IN BALANCED SOLUTIONS FOR SEED PLANTS

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In this paper it is proposed to give the results of several series of experiments designed primarily to determine the possible value of certain relatively insoluble salts in furnishing the necessary ions for the growth of seed plants. By means of such salts it will also be attempted to secure favorable combinations of the necessary ions. Throughout this discussion "insoluble" may be used in a very general sense, to include many salts soluble only to a comparatively slight degree, or with difficulty soluble, in water at from 15 to 25° C.

It is well known that in the soil a relatively small part of the salts ordinarily designated mineral nutrients is present in soluble form. There is, in general, a very considerable reserve or "unavailable" supply of the less readily soluble salts of such elements as K, Ca, Mg, Fe, S, and P. Nitrates are generally present only in low concentration and the surplus nitrogen supply is usually in the form of organic compounds. It has seemed to the writer eminently desirable to determine, therefore, if a favorable nutrient solution for seed plants may not be arranged from combinations of some of these insoluble salts, thus in some measure imitating the chemical relations in the soil.

In favor of this endeavor it might be argued that should this prove possible it would only be necessary to add to the culture vessel a surplus of the substances required. A small amount of that added would go into solution immediately and when an equilibrium were attained the absorption of any ions by the root would be compensated for by further solution of the substances furnishing these ions, and thus the equilibrium might be maintained and the concentration kept fairly constant over considerable intervals. Obviously, it would be impracticable to furnish nitrate as an insoluble compound, since the nitrates of

the bases required are all soluble to a high degree. If, therefore, nitrogen is furnished as NO_3 , the salt furnishing this ion would necessarily be added periodically, and to this extent the concentration would change from day to day. Relatively insoluble salts of ammonium are obtainable, however, such as MgNH_4PO_4 , and this salt has been employed in some of the experiments.

In the various experiments which have thus far been undertaken the sources of Ca are as follows: $\text{CaSO}_4 + 2\text{H}_2\text{O}$, CaCO_3 , $\text{Ca}_3(\text{PO}_4)_2$, and $\text{CaHPO}_4 + 2\text{H}_2\text{O}$; of Mg: $\text{MgSO}_4 + 7\text{H}_2\text{O}$, MgCO_3 , $\text{Mg}_3(\text{PO}_4)_2 + 8\text{H}_2\text{O}$, and $\text{MgNH}_4\text{PO}_4 + 6\text{H}_2\text{O}$; of K: KNO_3 and K_3PO_4 ; of Fe: $\text{FePO}_4 + 4\text{H}_2\text{O}$, $\text{FeC}_2\text{O}_4 + 2\text{H}_2\text{O}$, ferric citrate, and "soluble ferric phosphate." Certain other salts which might have been employed to advantage were not available at the time.

Among the more soluble of the salts included in this category are $\text{CaSO}_4 + 2\text{H}_2\text{O}$ having a solubility of 0.241 and 0.222 in 100 parts of water at 0° and at 100°C . respectively, and among the more insoluble salts are $\text{FePO}_4 + 4\text{H}_2\text{O}$ and CaCO_3 . One of the chief reasons for burdening the experiments with such a variety of substances may be found in the fact of their diverse solubilities; and inasmuch as the antagonistic relations of the ions in respect to the plant require consideration and are involved with osmotic and nutritive relations, such a variety of combinations was necessary in order to feel assured that some of the results obtained might be among the most favorable that such types of combinations could yield.

It is obvious that at no instant is the exact concentration of any salt known in such combinations, except approximately, in cases where soluble salts were added. However, the total concentration is readily determinable, likewise the electrolytic conductivity of the solution. One may also estimate the partial concentrations. When soluble salts are employed in nutrient solutions, the proportion of the ions is disturbed from the moment that the roots are introduced, and there is a progressive decrease in concentration until the solution is renewed. Likewise the differences in the proportion of the ions, determined, of course, by the differential absorption rates, are not continually reestablished by any form of "reserve." It would, of course,

be possible to effect a circulation of fresh nutrient solutions where soluble salts are employed, but any operation of this nature would be impracticable in most of our experimental work. After all, the problem is to obtain a combination of salts favorable to a high degree which may be employed in practically any type of experiment where the desire is to maintain the plant under satisfactory physiological conditions. If the labor involved is great in the one case and small in the other the one involving the less labor will, of course, be selected as the more practicable.

Before describing in detail the methods and experiments to be discussed it should be pointed out that the nutrient solution developed by Crone ('03) and considered by him to have certain advantages over the Pfeffer solution, contained, in addition to KNO_3 , MgSO_4 , and CaSO_4 , ferrous phosphate and tribasic calcium phosphate. The two salts last mentioned are, of course, relatively insoluble and were used by Crone with the idea of diminishing the chlorosis which he attributed to the excess of soluble phosphate and the low content of iron. Later, however, Benecke ('09) was unable to substantiate the claims made by Crone as to the benefits to be derived from the type of solution which the latter had formulated.

The experiments on which the data in table 1 are based were carried out in the experimental greenhouse at the Missouri Botanical Garden during April, 1920. The methods employed were in fairly close accord with those previously described. Glass tumblers of 250 cc. capacity were used with 240 cc. of nutrient solution. To these containers were fitted corks 7.5 cm. in diameter and 0.7 cm. in thickness, arranged with holes for the insertion of the roots of the seedlings, and with an extra hole to facilitate the addition of water lost by transpiration. The seedlings were germinated over water, and in order to insure the greatest possible uniformity in size a selection of these was made when the shoots were about 2 cm. in height. Each cork was held in position by a stout rubber band passing around the tumbler lengthwise. The tumblers were covered as usual to protect the roots from the light, and the cultures were then freely and equally exposed on a lattice bench in the greenhouse. The variety of wheat employed throughout was the Pacific Coast Blue Stem,

supplied by the Plant Introduction Garden of the Bureau of Plant Industry, Chico, California. The corn was a standard field strain of yellow Dent.

The results shown in tables II and III¹ were obtained at Carmel, California, during July and August of the same year. At Carmel the cultures were arranged on lattice tables in the open. The average temperature was about 15.6° C. and the average daily evaporation from a standard spherical porous cup at-mometer about 15 cc. Table II represents cultures prepared exactly as in table I except that glass beakers, of the same capacity, were used instead of tumblers. The data in table III are from experiments closely paralleling those represented by table II except that in the former the containers used were one-quart preserving jars (Economy style). This type of jar proved most convenient in this work, since the mouth of the jar is large, taking the same corks as used in the tumblers and beakers. Moreover, the spring clips which accompany these jars afford a handy method of fastening the cork to the jar so that the seedlings are not readily disturbed. The use of the larger containers in this case explains the larger quantities of salts or solutions employed, and, of course, vessels of this capacity permit the experiments to be continued over a longer period of time.

Inasmuch as certain cultures in each of these series contained not only a full mineral "nutrient" solution but also some citrate, it seemed well to arrange all the solutions and then let them stand two days in case some evidence of fermentation might develop. This occurred in certain cases especially in the second and third series, but afterwards cleared up. The significance of this will be discussed in a later paper in which the physical characteristics of nutrient solutions in general will receive special consideration.

In all cases where readily soluble salts were used in these experiments the initial quantities in the different series varied considerably, as also the quantities added from time to time,

¹ This work was done at the Coastal Laboratory of the Carnegie Institution of Washington. The writer is pleased to make acknowledgment of the facilities and coöperation extended by Doctor D. T. MacDougal, Director of Botanical Research, and of the courtesies of other members of the staff.

and these facts are brought out in the special explanations given in connection with the particular tables.

In table 1 there are given in the second and third columns (under "concentration," I and II) the quantities of the salts used, these being expressed in grams of the pure salt or in cc. of a standard stock solution. The concentration numbers occur again in the fifth column, indicating to which concentration the data in the remaining columns refer. When given in grams, the quantities indicated were used in 240 cc. of water, and no change of these constituents was made throughout the interval of growth.

The quantities given in cc. also require explanation. KNO_3 : the stock solution employed for every culture in which this salt occurs except No. 15 contains 35 grams KNO_3 in 1000 cc. of water, and the use of 10 cc. per culture of 240 cc. gives a concentration of this salt in the culture solution approximately three times as great as in solution B (No. 15 in this table). It is approximately two-thirds as strong as the concentration of KNO_3 in one of the "best" cultures of Livingston and Tottingham ('18), that is, R_6C_1 , referred to in my earlier paper (Duggar, '20) as solution C. Moreover, in the two cultures (No. 12 and No. 14) in which $\text{Mg}(\text{NO}_3)_2$ or NaNO_3 was substituted for KNO_3 , the strength of the solution was such as to afford a quantity of NO_3 equivalent to that of the KNO_3 in all cultures except No. 15. MgSO_4 : the stock solution, 12 grams in 1000 cc. of water, is the same as that used in solution B (No. 15 of this series). The concentration of soluble ferric phosphate is likewise made the same as in solution B (No. 15 of this table). The control solution in this series is solution B, No. 15 of the table, previously described in detail, as noted above. Additions of 10 cc. of KNO_3 were made to each culture (240 cc.) containing this salt at intervals of 7 days, and at the same time the solution in No. 15 (solution B, control) was renewed.

A glance at table 1, and more especially a study of fig. 1 (wheat), indicates that the differences between the two "concentrations" or strengths of solutions are within the probable limits of variation commonly found in duplicate cultures. The average of the two similar control cultures in solution B (No. 15) is exceeded by No. 2. The latter culture differs from the control

TABLE I

GROWTH OF WHEAT AND CORN IN SOLUTIONS OF RELATIVELY INSOLUBLE SALTS. THE GROWTH QUANTITIES REPRESENT, FOR WHEAT, 10 PLANTS, AND FOR CORN, 8 PLANTS; PERIOD OF CULTURE, 21 DAYS

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Kind of plant	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II						Init.	Fin.
1	.125 gm.	.25 gm.	CaSO ₄ +2H ₂ O Mg ₃ (PO ₄) ₂ +8H ₂ O FePO ₄ +4H ₂ O KNO ₃	I 10.20	Wheat	5.70	4.50	6.9	7.5
	.125 gm.	.50 gm.		II 14.00	Wheat	8.60	5.40	6.9	7.5
	.125 gm.	.25 gm.		I 35.90	Corn	24.20	11.70	6.9	8.4
	10 cc.	10 cc.		II 33.60	Corn	25.20	8.40	6.9	7.3
2	.125 gm.	.25 gm.	CaSO ₄ +2H ₂ O Mg ₃ (PO ₄) ₂ +8H ₂ O Sol. ferric phosphate KNO ₃	I 17.10	Wheat	10.10	7.00	7.0	8.5
	.125 gm.	.50 gm.		II 17.80	Wheat	10.50	7.30	7.0	8.5
	40 cc.	40 cc.		I 35.85	Corn	25.70	10.15	7.0	8.3
	10 cc.	10 cc.		II 35.95	Corn	26.95	9.00	7.0	7.4
3	.25 gm.	.50 gm.	CaCO ₃ MgSO ₄ +7H ₂ O FePO ₄ +4H ₂ O KNO ₃	I 10.40	Wheat	5.50	4.90	7.2	7.7
	10 cc.	10 cc.		II 8.45	Wheat	5.10	3.35	7.2	7.4
	.125 gm.	.25 gm.		I 35.40	Corn	22.45	12.95	7.2	7.2
	10 cc.	10 cc.		II 35.25	Corn	26.10	9.15	7.2	7.4
4	.25 gm.	.50 gm.	CaCO ₃ MgSO ₄ +7H ₂ O Sol. ferric phosphate KNO ₃	I 15.00	Wheat	8.10	6.90	7.3	8.3
	10 cc.	10 cc.		II 12.40	Wheat	7.60	4.80	7.3	7.5
	40 cc.	40 cc.		I 41.85	Corn	27.25	14.60	7.3	7.3
	10 cc.	10 cc.		II 36.10	Corn	25.15	10.95	7.3	7.4
5	.125 gm.	.25 gm.	CaSO ₄ +2H ₂ O MgCO ₃ FePO ₄ +4H ₂ O KNO ₃	I 8.80	Wheat	5.50	3.30	8.5	7.3
	.125 gm.	.25 gm.		II 8.80	Wheat	5.00	3.80	8.0	8.6
	.125 gm.	.25 gm.		I 32.50	Corn	23.85	8.65	8.5	8.5
	10 cc.	10 cc.		II 31.85	Corn	23.10	8.75	8.0	8.5

TABLE I—Continued

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Kind of plant	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II						Init.	Fin.
6	.125 gm.	.25 gm.	CaSO ₄ +2H ₂ O MgCO ₃ Sol. ferric phosphate KNO ₃	I 12.00	Wheat	7.60	4.40	8.3	8.7
	.125 gm.	.25 gm.		II 9.70	Wheat	5.90	3.80	7.9	8.7
	40 cc.	40 cc.		I 38.10	Corn	26.30	11.80	8.3	8.4
	10 cc.	10 cc.		II 34.85	Corn	25.90	8.95	7.9	8.8
7	.125 gm.	.25 gm.	CaHPO ₄ +2H ₂ O MgSO ₄ +7H ₂ O FePO ₄ +4H ₂ O KNO ₃	I 12.80	Wheat	6.80	6.60	6.4	8.5
	10 cc.	10 cc.		II 11.45	Wheat	7.20	4.25	6.3	8.3
	.125 gm.	.25 gm.		I 34.06	Corn	23.37	10.69	6.4	8.5
	10 cc.	10 cc.		II 41.45	Corn	28.70	12.75	6.3	7.4
8	.125 gm.	.25 gm.	CaHPO ₄ +2H ₂ O MgSO ₄ +7H ₂ O Sol. ferric phosphate KNO ₃	I 15.60	Wheat	9.00	6.60	6.8	8.8
	10 cc.	10 cc.		II 14.10	Wheat	8.90	5.20	6.6	8.3
	40 cc.	40 cc.		I 38.29	Corn	26.17	12.17	6.8	8.5
	10 cc.	10 cc.		II 41.90	Corn	27.40	14.50	6.6	8.1
9	.125 gm.	.25 gm.	CaHPO ₄ +2H ₂ O MgSO ₄ +7H ₂ O FeC ₂ O ₄ +2H ₂ O KNO ₃	I 8.10	Wheat	4.20	3.90	5.5	7.5
	10 cc.	10 cc.		II 8.00	Wheat	4.05	3.95	5.3	7.2
	.125 gm.	.25 gm.		I 25.55	Corn	17.95	7.60	5.5	8.5
	10 cc.	10 cc.		II 26.25	Corn	18.35	7.90	5.3	8.3
10	.25 gm.	.50 gm.	MgNH ₄ PO ₄ +6H ₂ O CaSO ₄ +2H ₂ O Sol. ferric phosphate KNO ₃	I 14.00	Wheat	8.90	5.10	7.3	7.4
	.125 gm.	.25 gm.		II 15.90	Wheat	10.90	5.00	7.2	7.2
	40 cc.	40 cc.		I 34.15	Corn	22.45	11.70	7.3	8.3
	10 cc.	10 cc.		II 35.45	Corn	25.80	9.65	7.2	7.4

TABLE I—Continued

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Kind of plant	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II						Init.	Fin.
11	.25 gm.	.50 gm.	$\left. \begin{array}{l} \text{MgNH}_4\text{PO}_4 + 6\text{H}_2\text{O} \\ \text{CaSO}_4 + 2\text{H}_2\text{O} \\ \text{FePO}_4 + 4\text{H}_2\text{O} \\ \text{KNO}_3 \end{array} \right\}$	I 7.00	Wheat	4.70	2.30	7.1	7.4
	.125 gm.	.25 gm.		II 7.10	Wheat	4.90	2.20	7.1	7.4
	.125 gm.	.25 gm.		I 31.60	Corn	24.00	7.60	7.1	7.6
	10 cc.	10 cc.		II 34.63	Corn	27.53	7.10	7.1	7.3
12	.25 gm.	.50 gm.	$\left. \begin{array}{l} \text{K}_3\text{PO}_4 \\ \text{CaSO}_4 + 2\text{H}_2\text{O} \\ \text{FePO}_4 + 4\text{H}_2\text{O} \\ \text{Mg}(\text{NO}_3)_2 + 6\text{H}_2\text{O} \end{array} \right\}$	I 4.60	Wheat	2.80	1.80	7.2	7.3
	.125 gm.	.25 gm.		II 2.61	Wheat	1.61	1.00	7.4	7.4
	.125 gm.	.50 gm.		I 17.65	Corn	13.80	3.85	7.2	8.5
	10 cc.	10 cc.		II 16.80	Corn	12.60	4.20	7.4	7.5
13	.25 gm.	.50 gm.	$\left. \begin{array}{l} \text{K}_3\text{PO}_4 \\ \text{CaSO}_4 + 2\text{H}_2\text{O} \\ \text{FeC}_2\text{O}_4 + 2\text{H}_2\text{O} \\ \text{MgNH}_4\text{PO}_4 + 6\text{H}_2\text{O} \end{array} \right\}$	I 5.67	Wheat	3.89	1.78	8.6	7.6
	.125 gm.	.25 gm.		II 5.33	Wheat	3.72	1.61	8.6	7.6
	.125 gm.	.25 gm.		I 25.55	Corn	19.15	6.40	8.6	8.6
	.25 gm.	.50 gm.		II 26.70	Corn	20.30	6.40	8.6	7.4
14	.25 gm.	.50 gm.	$\left. \begin{array}{l} \text{K}_3\text{PO}_4 \\ \text{CaSO}_4 + 2\text{H}_2\text{O} \\ \text{FePO}_4 + 4\text{H}_2\text{O} \\ \text{MgNH}_4\text{PO}_4 + 6\text{H}_2\text{O} \\ \text{NaNO}_3 \end{array} \right\}$	I 2.15	Wheat	1.60	.55	9.0+	8.2
	.125 gm.	.25 gm.		II —	Wheat	—	—	9.0+	8.3
	.125 gm.	.25 gm.		I 14.90	Corn	11.50	2.40	9.0+	8.4
	.25 gm.	.50 gm.		II 12.90	Corn	8.45	4.45	9.0+	8.4
15	10 cc.	10 cc.	$\left. \begin{array}{l} \text{CaSO}_4 + 2\text{H}_2\text{O} \\ \text{MgSO}_4 + 7\text{H}_2\text{O} \\ \text{Sol. ferric phosphate} \\ \text{KNO}_3 \end{array} \right\}$	I 14.70	Wheat	7.80	6.90	6.9	7.3
	30 cc.	30 cc.		II 17.35	Wheat	9.75	7.60	6.9	7.6
	40 cc.	40 cc.		I 30.60	Corn	20.50	10.10	6.9	7.5
	10 cc.	10 cc.		II 25.40	Corn	17.80	7.60	6.9	7.2

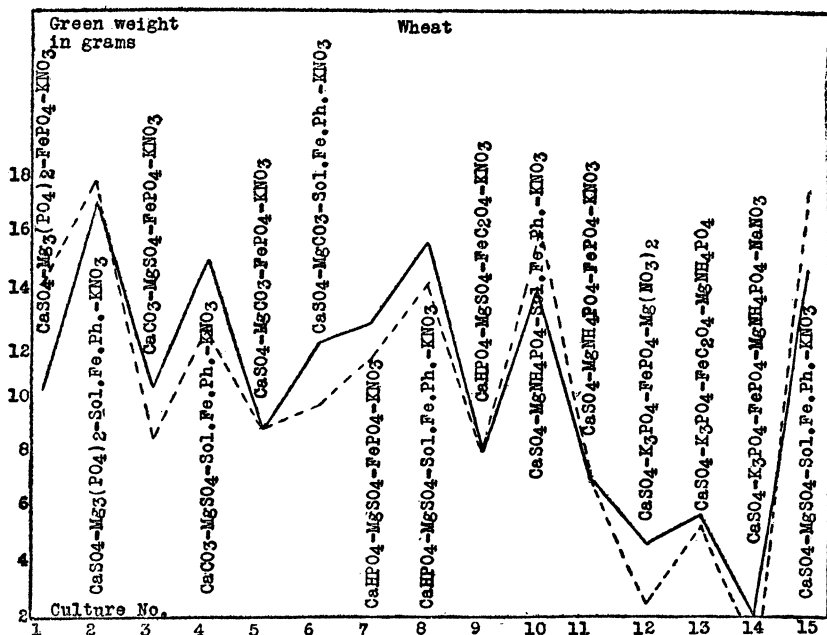


Fig. 1. Yield of wheat in solutions of relatively insoluble salts. Continuous line is concentration I and broken line concentration II (see table 1).

(1) in the excess of CaSO_4 (solid phase present), (2) in the substitution of the "insoluble" tribasic magnesium phosphate for the soluble MgSO_4 , and (3) in the greater content of KNO_3 . It will be noticed also that cultures 4, 8, and 10 approach the value of the control, and all of these contain the soluble ferric phosphate, combined with various calcium and magnesium compounds. No culture containing either K_3PO_4 or iron oxalate has yielded satisfactorily. Similarly, MgCO_3 in the combinations employed would seem to be less depressing than K_3PO_4 but still unfavorable. Among the cultures mentioned as giving the higher yields no striking peculiarity was noted except in the case of No. 10, in which there was pronounced tillering at a relatively early period.

With corn many cultures are ahead of the control, No. 15, and those in advance are again generally the cultures containing soluble ferric phosphate, though the differences between the pairs containing FePO_4 and the salt of iron just mentioned

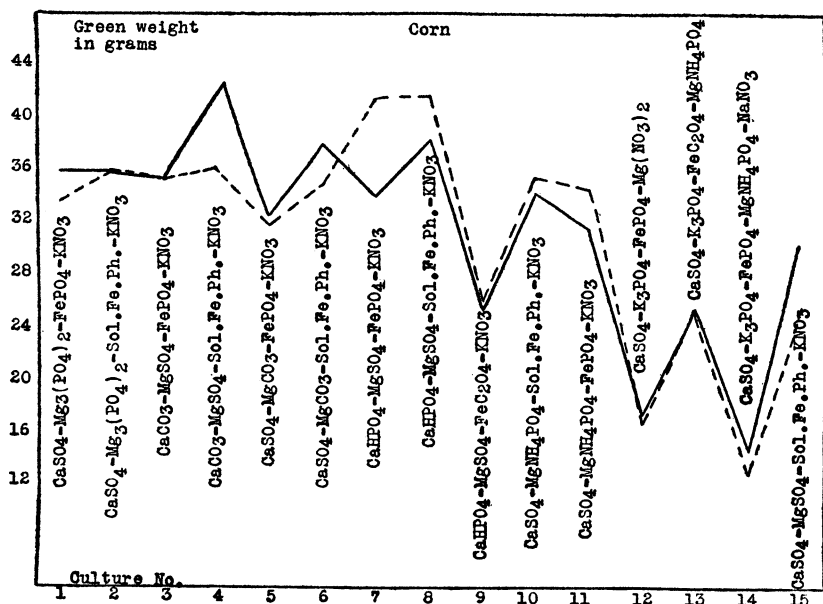


Fig. 2. Yield of corn in solutions of relatively insoluble salts. Continuous line is concentration I and broken line concentration II (see table I).

are not so striking as with wheat. Nor is it to be assumed that this relation will necessarily hold under all conditions. Moreover, corn, notably resistant to Mg salts, does not exhibit some of the antagonistic effects evident in the case of wheat. No. 11 showed pronounced chlorosis, followed, but to a somewhat less extent, by Nos. 7, 1, 12, 10, 13, and 14. Nos. 2-6, 8, and 15 were normal in appearance, while No. 9 was intensely green.

Difference in "concentration" in the first series was wholly in respect to a variation in the quantity of the relatively insoluble salts; but inasmuch as a considerable amount of the insoluble residue remained in each culture at the close of the experiment it would seem improbable that any difference in the amount of the solid phase would affect the yields. Accordingly, in the series carried out at Carmel, table II and fig. 3, it will be seen that the following are practically the only ways in which the "concentrations" are varied: (1) in column "II" the quantity of KNO_3 is one-half the amount used in column "I," and (2) in column "III," while the amount of nitrate remains

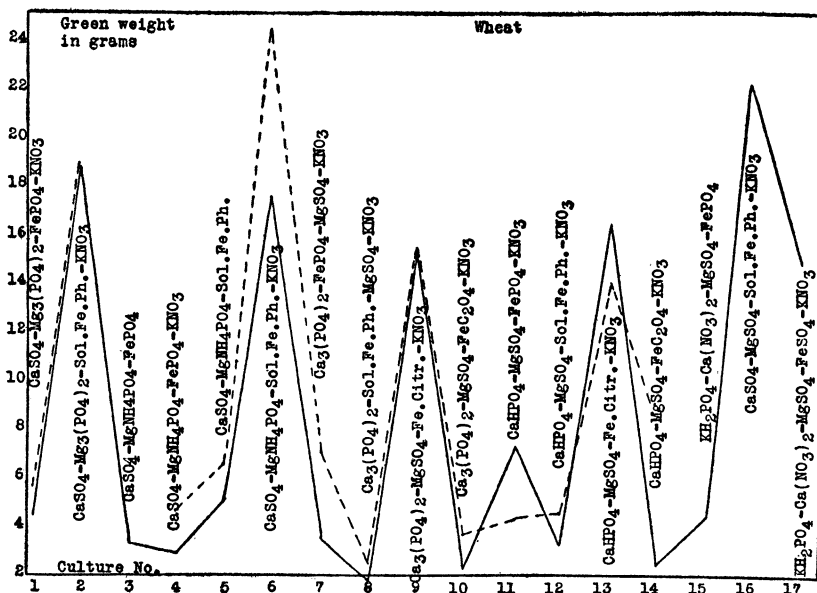


Fig. 3. Yield of wheat in solutions of relatively insoluble salts. Continuous line is concentration I and broken line concentration II (see table II).

as in "I," the quantity of the iron salt is reduced to one-half. The concentration of KNO_3 was the same as in the experiments given in table I. The stock solution of MgSO_4 contained 41.932 grams of the salt in 1 liter of water, so that 10 cc. per culture of 240 cc. gave a solution two-thirds as strong in MgSO_4 as the R_6C_1 of Livingston and Tottingham ('18). In almost every instance where the growth quantities are small the lower concentrations of the potassium nitrate and of the magnesium sulphate have a tendency within the same culture number to promote the greater growth. In this series the best culture containing insoluble salts is No. 6 (CaSO_4 , [solid phase present], MgNH_4PO_4 , soluble ferric phosphate, and KNO_3), followed closely by culture 2, the latter being the same that proved so satisfactory in the previous series.

As will be pointed out later, the more insoluble calcium salts give the higher yields when in combination with relatively insoluble salts of magnesium. This is true except in certain cases where iron citrate enters into the combination. In certain cul-

TABLE II—Continued

Cult. No.	Concentration			Salts used	Total gr. wt. gms.	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II	III					Init.	Fin.
11	.125 gm.	.125 gm.		CaHPO ₄ +2H ₂ O FePO ₄ +4H ₂ O MgSO ₄ +7H ₂ O KNO ₃	I 7.22	4.62	2.60	6.4	8.0
	.125 gm.	.125 gm.			II 4.43	2.97	1.46	6.6	8.0
	10 cc.	5 cc.							
	10 cc.	5 cc.							
12	.125 gm.	.125 gm.	.125 gm.	CaHPO ₄ +2H ₂ O Sol. ferric phosphate MgSO ₄ +7H ₂ O KNO ₃	I 3.25	2.18	1.07	5.6	7.8
	.25 gm.	.25 gm.	.125 gm.		II 4.61	2.80	1.81	5.6	7.9
	10 cc.	5 cc.	10 cc.		III 6.08	3.73	2.35	—	8.0
	10 cc.	5 cc.	10 cc.						
13	.125 gm.	.125 gm.	.125 gm.	CaHPO ₄ +2H ₂ O Ferric citrate MgSO ₄ +7H ₂ O KNO ₃	I 16.41	11.36	5.05	5.8	8.0
	.25 gm.	.25 gm.	.125 gm.		II 13.96	9.60	4.36	5.8	7.9
	10 cc.	5 cc.	10 cc.		III 17.85	12.67	5.18	—	8.0
	10 cc.	5 cc.	10 cc.						
14	.125 gm.	.125 gm.	.125 gm.	CaHPO ₄ +2H ₂ O FeC ₂ O ₄ +2H ₂ O MgSO ₄ +7H ₂ O KNO ₃	I 2.41	1.46	.95	5.6	7.6
	.125 gm.	.125 gm.	.0625 gm.		II 8.43	4.77	3.66	5.6	8.0
	10 cc.	5 cc.	10 cc.		III 4.71	2.70	2.01	—	7.6
	10 cc.	5 cc.	10 cc.						
15				Solution A	4.56	2.87	1.69	—	5.2
16				Solution B	22.20	13.62	8.58	—	7.6
17				Tottingham's sol.	14.49	9.95	4.54	—	6.4

tures where the magnesium salt is the more soluble, Nos. 8-13, the more favorable action of ferric citrate as contrasted with the soluble ferric phosphate and FePO_4 in these cultures with wheat is clearly shown. With the exceptions noted the favorable influence of soluble ferric phosphate in the solution is evident, especially in Nos. 2 and 6, as also, of course, in solution B.

The Tottingham solution was exceeded by 5 combinations. The Shive solution, solution A (No. 15) was unsatisfactory in this series, since after being set up it was found that the acidity was much higher than usual. In these experiments, however, no recrystallization of the salts employed was carried out and no corrections for acidity were made.

The six cultures giving the higher yields (Nos. 2, 6, 9, 13, 16, and 17) were all green and healthy in appearance. Cultures 3 and 5, without KNO_3 , were characterized by marked attenuation; No. 14 exhibited excessive greening; and Nos. 7 and 15 were abnormally stocky in general appearance.

As stated previously, the experiments shown in table III and in fig. 4 were also obtained at Carmel. The experiments were set up on July 10, using wheat as a test plant and employing quart jars as containers. For cultures 1-20 the same stock solutions of KNO_3 and MgSO_4 as described for table II were used. The results are not in entire agreement with those given in table II. This may be accounted for in part by the use of the larger containers and also in part by differences in weather conditions. During the progress of the experiments here discussed, there were several days of comparatively warm weather without fog, inducing high evaporation rates. It is well to note also that a slight mishap to culture 2, which was found upset one morning, may be responsible in some measure for the low yield of this culture.

Renewals of the solutions in the control cultures (Nos. 21-23) were made about every 10 days. Additional amounts of KNO_3 , 20 cc. in the case of all cultures in column "I" and 10 cc. in the case of column "II," were added on July 24 and August 6. No additional MgSO_4 was added to the cultures receiving this salt until August 6, when 10 cc. were given each of those receiving this salt in column "I," and 5 cc. for similar cultures in column "II." With the larger amount of nitrate employed, cul-

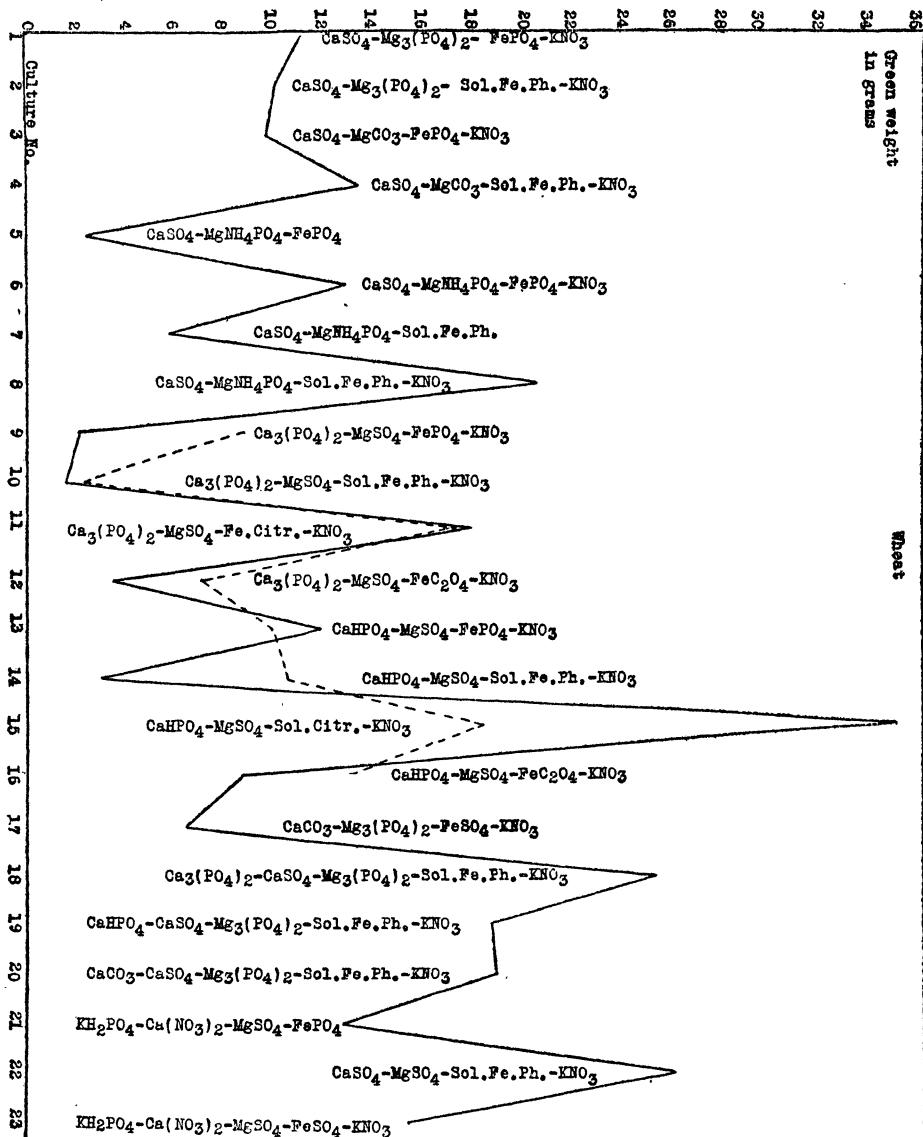


Fig. 4. Yield of wheat in solutions of relatively insoluble salts. Continuous line is concentration I and broken line concentration II (see table III).

ture 15 (CaHPO_4 , MgSO_4 , ferric citrate, and KNO_3) is best, followed by one of the controls, solution B, and this in turn is very closely followed by Nos. 18, 8, 20, 19, and 11. Cultures 11 and 15 confirm the previous experience that the ferric citrate effects a high degree of balance in cases where the magnesium salt is more soluble than the calcium salt used; and neither the soluble ferric phosphate nor the FePO_4 can replace it in this respect where wheat is the test plant (compare with the cultures above mentioned Nos. 9, 10, 13, and 14).

With due consideration of the causes already mentioned the value of the soluble ferric phosphate in the culture media is confirmed, and the importance of ferric citrate established in certain combinations. No experiments thus far made have thrown any special light on the nature of the benefit derived in these cases from the soluble ferric phosphate or the iron citrate. In both cases, however, within the range of reaction involved in the studies here reported, suspension films consisting in part at least of ferric hydroxide are thrown down. The writer is now endeavoring to determine if floating particles of this type, or a substance in the colloidal state may possibly be of importance in the absorption and distribution of the ions. I have previously mentioned this possibility (Duggar, '20, p. 42) while referring especially to certain experiments of Bonazzi and of Allen on the culture of microorganisms.

SUMMARY

The value of certain relatively insoluble salts as sources of the necessary ions for the growth of seed plants has been tested in a variety of combinations covering by no means, however, the entire range of possibility.

It is argued that in certain types of work many advantages may accrue from the use of combinations of insoluble salts, because of (1) the tendency to maintain a constant concentration of the various ions furnished, and also because (2) no renewal of the solution (except as to the addition of NO_3) is required from day to day.

As sources of Ca, Mg, Fe, PO_4 , SO_4 , many insoluble salts have been tested, but no salt of this type is procurable as a practical source of NO_3 , so that in most experiments this ion is furnished by KNO_3 .

TABLE III

GROWTH OF WHEAT IN SOLUTIONS OF RELATIVELY INSOLUBLE SALTS. THE GROWTH QUANTITIES REPRESENT 8 PLANTS: PERIOD OF CULTURE, 40 DAYS; VOLUME OF CULTURE SOLUTION, 890 cc.

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II					Init.	Fin.
1	.5 gm. .5 gm. 1.0 gm. 40 cc.		CaSO ₄ +2H ₂ O FePO ₄ +4H ₂ O Mg ₃ (PO ₄) ₂ +8H ₂ O KNO ₃	I 11.20	6.58	4.62	7.0	7.8
2	.5 gm. 1.0 gm. 1.0 gm. 40 cc.		CaSO ₄ +2H ₂ O Sol. ferric phosphate Mg ₃ (PO ₄) ₂ +8H ₂ O KNO ₃	I 10.20	6.01	4.19	8.0	7.9
3	.5 gm. .5 gm. .5 gm. 40 cc.		CaSO ₄ +2H ₂ O FePO ₄ +4H ₂ O MgCO ₃ KNO ₃	I 9.86	5.79	4.07	9.0	7.6
4	.5 gm. 1.0 gm. .5 gm. 40 cc.		CaSO ₄ +2H ₂ O Sol. ferric phosphate MgCO ₃ KNO ₃	I 13.47	8.85	4.62	8.8	8.0
5	.5 gm. .5 gm. .5 gm.		CaSO ₄ +2H ₂ O FePO ₄ +4H ₂ O MgNH ₄ PO ₄ +6H ₂ O	I 2.40	1.42	.98	7.1	6.4
6	.5 gm .5 gm .5 gm. 40 cc.		CaSO ₄ +2H ₂ O FePO ₄ +4H ₂ O MgNH ₄ PO ₄ +6H ₂ O KNO ₃	I 12.90	7.72	5.18	6.9	7.4
7	.5 gm. 1.0 gm. .5 gm.		CaSO ₄ +2H ₂ O Sol. ferric phosphate MgNH ₄ PO ₄ +6H ₂ O	I 5.85	2.62	3.23	7.3	7.3
8	.5 gm. 1.0 gm. .5 gm. 40 cc.		CaSO ₄ +2H ₂ O Sol. ferric phosphate MgNH ₄ PO ₄ +6H ₂ O KNO ₃	I 20.72	12.05	8.67	8.1	7.2
9	1.0 gm. .5 gm. 40 cc. 40 cc.	1.0 gm. .5 gm. 20 cc. 20 cc.	Ca ₃ (PO ₄) ₂ FePO ₄ +4H ₂ O MgSO ₄ +7H ₂ O KNO ₃	I 2.08 II 8.83	1.28 5.77	.80 3.06	—	7.6 7.4
	1.0 gm. 1.0 gm. 40 cc. 40 cc.	1.0 gm. 1.0 gm. 20 cc. 20 cc.	Ca ₃ (PO ₄) ₂ Sol. ferric phosphate MgSO ₄ +7H ₂ O KNO ₃	I 1.64 II 2.32	1.11 1.72	.53 .60	8.0	7.7 7.7

TABLE III—*Continued*

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II					Init.	Fin.
11	1.0 gm.	1.0 gm.	Ca ₃ (PO ₄) ₂	I 18.02 II 17.31	11.97 9.86	6.05 7.45	8.3	7.9 8.0
	1.0 gm.	1.0 gm.	Ferric citrate					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
12	1.0 gm.	1.0 gm.	Ca ₃ (PO ₄) ₂	I 3.48 II 7.12	2.12 3.67	1.36 3.45	6.2	7.5 7.6
	.5 gm.	.5 gm.	FeC ₂ O ₄ +2H ₂ O					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
13	.5 gm.	.5 gm.	CaHPO ₄ +2H ₂ O	I 11.87 II 10.00	7.72 6.83	4.15 3.17	6.6	7.6 7.5
	.5 gm.	.5 gm.	FePO ₄ +4H ₂ O					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
14	.5 gm.	.5 gm.	CaHPO ₄ +2H ₂ O	I 2.97 II 10.67	2.07 7.19	.90 3.48	7.9	7.9 7.8
	1.0 gm.	1.0 gm.	Sol. ferric phosphate					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
15	.5 gm.	.5 gm.	CaHPO ₄ +2H ₂ O	I 35.30 II 18.55	22.63 11.13	12.67 7.42	8.1 7.3	8.0 7.9
	1.0 gm.	1.0 gm.	Ferric citrate					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
16	.5 gm.	.5 gm.	CaHPO ₄ +2H ₂ O	I 8.80 II 13.14	5.99 3.09	2.81 6.00	6.7	7.9 7.8
	.5 gm.	.5 gm.	FeC ₂ O ₄ +2H ₂ O					
	40 cc.	20 cc.	MgSO ₄ +7H ₂ O					
	40 cc.	20 cc.	KNO ₃					
17	1.0 gm. trace		CaCO ₃	I 6.52	4.20	2.32	7.8	7.9
	.5 gm.		FeSO ₄					
	40 cc.		Mg ₃ (PO ₄) ₂ +8H ₂ O					
	40 cc.		KNO ₃					
18	1.0 gm.	1.0 gm.	Ca ₃ (PO ₄) ₂	I 25.55	16.82	8.73	8.0	7.9
	.5 gm.	.5 gm.	CaSO ₄ +2H ₂ O					
	1.0 gm.	1.0 gm.	Sol. ferric phosphate					
	.5 gm.	.5 gm.	Mg ₃ (PO ₄) ₂ +8H ₂ O					
	40 cc.	20 cc.	KNO ₃					
19	.5 gm.		CaHPO ₄ +2H ₂ O	I 18.99	12.58	6.41	7.8	8.0
	.5 gm.		CaSO ₄ +2H ₂ O					
	1.0 gm.		Sol. ferric phosphate					
	.5 gm.		Mg ₃ (PO ₄) ₂ +8H ₂ O					
	40 cc.		KNO ₃					

TABLE III—*Continued*

Cult. No.	Concentration		Salts used	Total gr. wt. gms.	Gr. wt. tops gms.	Gr. wt. roots gms.	P _H	
	I	II					Init.	Fin.
20	1.0 gm.		CaCO ₃	19.15	12.50	6.65	8.0	7.9
	.5 gm.		CaSO ₄ +2H ₂ O					
	1.0 gm.		Sol. ferric phosphate					
	.5 gm.		Mg ₃ (PO ₄) ₂ +8H ₂ O					
	40 cc.		KNO ₃					
21			Solution A	12.90	7.92	4.98	4.1	5.7
22			Solution B	26.23	15.16	11.07	6.6	7.7
23			Tottingham's sol.	15.55	9.20	6.35	5.8	6.4

A relatively insoluble source of NH₄ (MgNH₄PO₄) has been found unsatisfactory as a source of nitrogen with the test plants used.

In each of three series of cultures in which wheat or wheat and corn were used, one or more of the combinations containing two or more insoluble salts exceeded the growth in the best control culture employed. The best control culture contained CaSO₄, MgSO₄, soluble ferric phosphate, and KNO₃. Cultures exceeding the control contained in the several series the following combinations of salts: I, CaSO₄ (solid phase present), Mg, (PO₄)₂, soluble ferric phosphate, and KNO₃; II, CaSO₄ (solid phase present), MgNH₄PO₄, soluble ferric phosphate, and KNO₃; III, CaHPO₄, MgSO₄, ferric citrate, and KNO₃.

In all series, with the test plants mentioned, a group of cultures approached very closely the yields of the best combinations, and in all cases in such best combinations the calcium salt is relatively more soluble than the magnesium salt, except in certain combinations into which ferric citrate enters.

Soluble ferric phosphate has proved a valuable constituent in the culture medium in a variety of combinations. In certain

cases ferric citrate has proved equally valuable. Certain fermentation processes may occur in cultures in which these compounds are employed and a further study of the influence of those changes is necessary.

Except in the cultures containing K_3PO_4 or $MgCO_3$, the hydrogen-ion concentration of all combinations used in the three series here reported ranges from 5.6 to 8.0, and after the growth of test plants there is usually a shift in the P_H toward alkalinity or greater alkalinity.

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